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Abstract: *DT fuel loaded capsules at the National Ignition Facility (NIF) regularly produce sub-MeV "thermal" neutrons that can provide insight into implosion dynamics and open the possibility of measuring spectrum-averaged (n,γ) cross sections using ICF plasmas. In this paper we describe the development of a NIF-based Low Energy Neutron Spectrometer (LENS).*

1. Introduction

The National Ignition Facility (NIF) at LLNL has succeeded in achieving unprecedentedly high fuel areal density (ρR_{fuel}) values in excess of 1 g/cm^2 [1]. While the primary goal of this effort has been to trap the α-particle energy from the D+T reaction in order to achieve thermonuclear ignition, a fortuitous scientific side-effect is that a significant fraction of the 14 MeV neutrons from the D+T reaction scatter until they "thermalize" to the *keV* energies of the fuel itself. The number and spectral distribution of these thermal neutrons are excellent probes of the temperature and plasma confinement time of the cold fuel and potentially provide a window into the cold fuel entropy for the first time. In addition to their value as a plasma diagnostic, these neutrons are also ideally suited to studies of the neutron capture reactions that are responsible for the formation of the elements heavier than iron [2].

However, no capability currently exists at the NIF to measure neutrons with E_n < 140 keV. We have therefore undertaken an effort to build a *Low-Energy Neutron Spectrometer* (LENS) to measure downscattered neutrons down to *eV* energies. This development effort utilizes the intense, thick-target deuteron break-up neutron source at the Lawrence Berkeley National Laboratory (LBNL) 88-Inch Cyclotron to test novel neutron scintillator materials in a highly-segmented geometry designed to maximize signal bandwidth while minimizing ambient background arising from capture of scattered neutrons.

2. Low Energy Neutrons at NIF

An indirectly driven cryogenic NIF hohlraum+capsule is well suited to the production of low-energy neutrons. The NIF laser causes an explosive compression of a DT-loaded plastic capsule from an initial radius of 1 mm to a final value on the order of 30-40 µm. This compression forms a "cold" fuel layer with $\rho R_{fuel} \geq 1$ g/cm^2 and a temperature about 100 eV (>10^6 K) which causes 3-7% of the 14.1 MeV neutrons produced in the T(D,n)α reactions to scatter to energies between 10-12 MeV. The downscattered ratio (DSR) of the number of 10-12 MeV neutrons divided by the number of 13-15 MeV primary neutrons is the main diagnostic used to determine peak ρR_{fuel}. The capsule assembly remains confined for several hundreds of ps allowing 10^{-2}-10^{-3} of the neutrons to scatter multiple times down to energies that reflect the time-averaged temperature of the capsule constituents. Figure 1 shows a hydrodynamic simulation of a NIF shot in neutrons per MeV as a function of energy from the HYDRA code package. The simulation shows a low-energy "bump" corresponding to partially- and/or fully-thermalized neutrons which is well fit using a Maxwell-Boltzmann distribution with a temperature of 850 eV (red line).

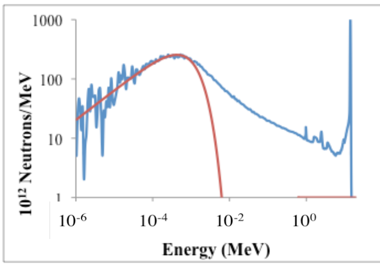

Figure 1: HYDRA neutron spectrum simulations for a typical NIF cryogenic shot (blue line) and a Maxwell-Boltzmann distribution for kT=850 eV (red line).

Experimental evidence for the existence of these low-energy neutrons comes from the observation of ^{198}Au arising from the neutron capture on the

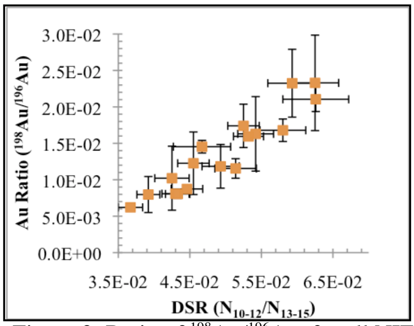

Figure 2: Ratio of ^{198}Au/^{196}Au for all NIF shots where SRC was fielded from Jan.-Sept. 2012 vs. the downscattered ratio (DSR) from NIF NTOF detectors.

≈100 mg of ^{197}Au in the hohlraum surrounding the NIF capsule. Low-energy neutrons are particularly effective at producing neutron capture products due to the increase in the neutron capture cross section with decreasing neutron energy. Figure 2 shows a plot of the ^{198}Au/^{196}Au ratio for hohlraum debris collected using the Solid Radchem (SRC) diagnostic at NIF vs. DSR for shots that took place between November 2011 and August 2012. The monotonic correlation in this plot suggests that the same mechanism, neutron scattering, is responsible for the generation of both 10-12 MeV and low-energy neutrons.

3. LENS design features

A LENS situated on one of the 20 m nToF lines at NIF would share many characteristics with the 960 channel LANSA (Large Neutron Scintillator Array) spectrometer designed by Cable et al. for use at the Nova laser [3]. However, a NIF-based LENS would measure the energy of incoming neutrons in current mode for neutrons with energies greater than a critical energy E_{crit} and then "cross-over" to individual pulse mode for lower neutron energies, functioning in a manner similar to LANSA. For energies below E_{crit}, LENS could be absolutely calibrated using a non-ICF neutron source in a manner similar to the existing NIF nToF system for energies above E_{crit} [4].

Individual LENS elements will contain materials with enhanced low-energy neutron response, such as the Li-doped glass employed at the GEKKO laser facility [5] or a commercially available Boron-loaded scintillator such as BC-454 from Saint-Gobain [6]. In addition to these materials we are exploring the use of a new class of Lithium-doped plastics being developed at LLNL by the group led by Dr. N. Zaitseva [7]. Each LENS element will be small enough to ensure that background from the Compton scatter of ambient neutron capture γ-rays could be removed through the use of a pulse-height threshold. Estimates using MCNP for the photon flux in the 20 m neutron alcove at NIF indicate that a 256-channel LENS comprised of 5 mm x 5 mm right cylindrical elements would accomplish these goals.

Figure 3 shows the ratio of the number of neutrons per μs on a single LENS element 20 m from the center of the NIF chamber for HYDRA simulations of capsules with confinement times of 1200 and 5000 ps relative to one with a confinement time of 400 ps. The difference in these curves for t>2 μs shows the ability of a LENS for determining plasma confinement times. In addition, the overall hit rate for a single LENS element never exceeds 1 event/10 ns indicating that pulse mode operation could potentially be possible for all neutron energies at these modest yields.

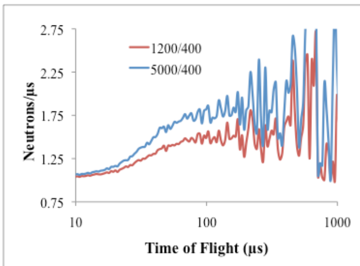

Figure 3: Simulations of the ratio of neutrons/μs for a LENS element for plasma confinement times of 1200 & 5000 ps compared to 400 ps from HYDRA.

The large number of LENS elements is ideally suited to the multi-anode photomultiplier tube (PMT) and digital electronic technologies. Leading candidates include the 64-channel HAMAMATSU H8500 PMT [8] and the CAEN V1740 64 channel VME digitizing units [9].

4. Conclusions

Design work has commenced for a highly segmented Low Energy Neutron Spectrometer (LENS) for use at NIF. LENS will provide unique insight into the dynamics of the plasma and enable ICF-based neutron capture cross section measurements. The LENS development and testing work is taking place using thick-target deuteron break-up and Li(p,n) neutron sources at the LBNL 88-Inch Cyclotron.

Acknowledgement

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